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MANNED TESTING OF FULLERTON SHERWOOD SIVA 55-VSW UNDERWATER BREATHING APPARATUS (UBA) FOR VERY SHALLOW WATER (VSW) MINE COUNTERMEASURE (MCM) MISSIONS

E. T. LONG

NOVEMBER 1999

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Submitted:	Reviewed:	Approved:
E. T. LONG LCDR, MC, USNR Principal Investigator	R. L. JOHNSON LCDR, USN Senior Projects Officer	E. N. CHRISTENSEN CDR, USN Commanding Officer

M. E. KNAFELC
CAPT, MC, USN
Medical Director

L. J. CREPEAU
Scientific Advisor

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Edwin T. Long, LCDR, MC, USNR

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Presently, no specific diving apparatus on the Authorized for Navy Use (ANU) list meets the demands set forth by the CNO to conduct very shallow water mine countermeasure (VSW MCM) operations. NEDU was tasked to test and evaluate the Fullerton Sherwood SIVA 55-VSW Underwater Breathing Apparatus (UBA), to determine whether it will maintain a sufficient O_2 fraction to support a working diver from the surface to 60 fsw (18.4 msw).

Using a 30% / 70% N_2 / O_2 mix, NEDU personnel conducted at least 16 SIVA 55 dives each in 77° ±3°F (25° ±1.7°C) water in the 15 ft (4.6 msw) deep NEDU test pool, and at 40 and 60 fsw (12.2 and 18.4 msw) in the NEDU Ocean Simulation Facility (OSF). Divers conducted manufacturer-sanctioned UBA purges on the surface and an additional purge after reaching the bottom, rested five to 10 minutes, then pedaled on underwater ergometers for 30 minutes each at 50 and 75 watts.

During test pool dives, nearly a quarter of the divers' UBAs reached potentially hypoxic levels. We conducted another set of test pool dives and determined that setting the "buoyancy control valve" (BCV) half-open—vice one-quarter open during the first series—ensured adequate UBA O_2 concentrations.

At 40 fsw nearly half of the divers' UBA PO_2 remained above 1.3 ATA after 10 minutes of exercise (mean = 1.34 ATA; range = 1.09 - 1.45 ATA) but, for all but one diver, dropped below 1.3 ATA within 13 minutes. Average PO_2 during the initial 10 minute rest period was 1.41 ATA. At 60 fsw we halted testing after four dives due to high PO_2 levels (mean = 1.63 ATA).

Because the U.S. Navy Diving Manual authorizes divers' PO_2 to reach 1.4 ATA without Commanding Officer (CO) authorization—and 1.6 ATA with CO authorization—we recommend that the SIVA 55-VSW be accepted and authorized for use by the VSW MCM detachment with the following caveats: (1) Never plan dives exceeding 40 fsw; (2) complete a thorough UBA purge prior to entering the water and before ascending; (3) for purposes of O_2 toxicity risk, diving as deep as 45 fsw (13.8 msw) is not considered an excursion; (4) total diving time deeper than 45 fsw is limited to 10 minutes; (5) at no time should this UBA be dived deeper than 50 fsw (15.3 msw); and (6) mission planning should rely on NEDU canister and gas bottle limits determined during unmanned studies. Finally, NEDU recommends renaming "buoyancy control valve" (BCV) with "variable exhaust valve" (VEV) to accurately reflect its function, and avoid confusing it with the integral buoyancy compensator.

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INTRODUCTION

In response to the continued inability of Explosive Ordnance Disposal (EOD) divers to conduct Mine Countermeasures (MCM) at depths between 10 to 40 feet of seawater (fsw; 3.1 to 12.2 meters of seawater (msw)), the Chief of Naval Operations (CNO) has authorized the Near Term Mine Warfare Campaign Plan. This plan includes establishing a Very Shallow Water (VSW) MCM Detachment as a primary supporting unit.

Presently, no specific diving apparatus on the Authorized for Navy Use (ANU) list meets the demands set forth by the CNO to conduct VSW MCM operations. The Navy Experimental Diving Unit (NEDU) has been tasked[1] to test and evaluate the Fullerton Sherwood SIVA 55-VSW Underwater Breathing Apparatus (UBA) to determine if it meets the stringent requirements for operating in this mission range.

NAVSEA Diving Safety Certification requirements must be met to achieve the designation of "Authorized for Navy Use" set forth by NAVSEA 00C prior to fielding any UBA in the U.S. Navy. This report deals with the conduct of manned diving tests and procedures to verify functional characteristics in accordance with manufacturer's specifications[2] and the VSW MCM UBA Performance Specification[3].

UBA DESCRIPTION

A representative drawing of the UBA is provided in Figure 1. The SIVA 55-VSW is a back-mounted, semi-closed circuit rebreather with two over-the-shoulder breathing bags (counterlungs) and two cummerbund-mounted quick-release weight pouches. The equally-sized inhalation and exhalation bags provide a combined volume of 7.5 liters. The UBA is designed to operate[2] using 100% oxygen, or any of the following nitrogen / oxygen (N_2 / O_2) gas mixes: 30% / 70%, 40% / 60%, 60% / 40%, or 67.5% / 32.5%. The U.S. Navy is primarily interested in the 30% / 70% O_2 gas mixture for use at a maximum working depth of 40 fsw (12.3 msw), the expected working depth range for the VSW MCM Detachment. The two 2.8 liter floodable volume flasks incorporate Deutch Industrial Number (DIN) type fittings, allowing a 3,500 psig (24,132 kPa) flask assembly rating. Gas is injected into the inhalation side counterlung through a metering valve adjusted to deliver 4.5 liters per minute (LPM); gas can also be added to the breathing loop via a manual add valve. The carbon dioxide (CO_2) absorbent canister holds approximately 5.5 lbs. (2.5 kg) of sodalime absorbent. However, based on the results and recommendations of NEDU unmanned testing[4], 6.8 ± 0.2 lbs (3.0 ± .01 kg) of absorbent was packed in the canister during these tests to prevent channeling.

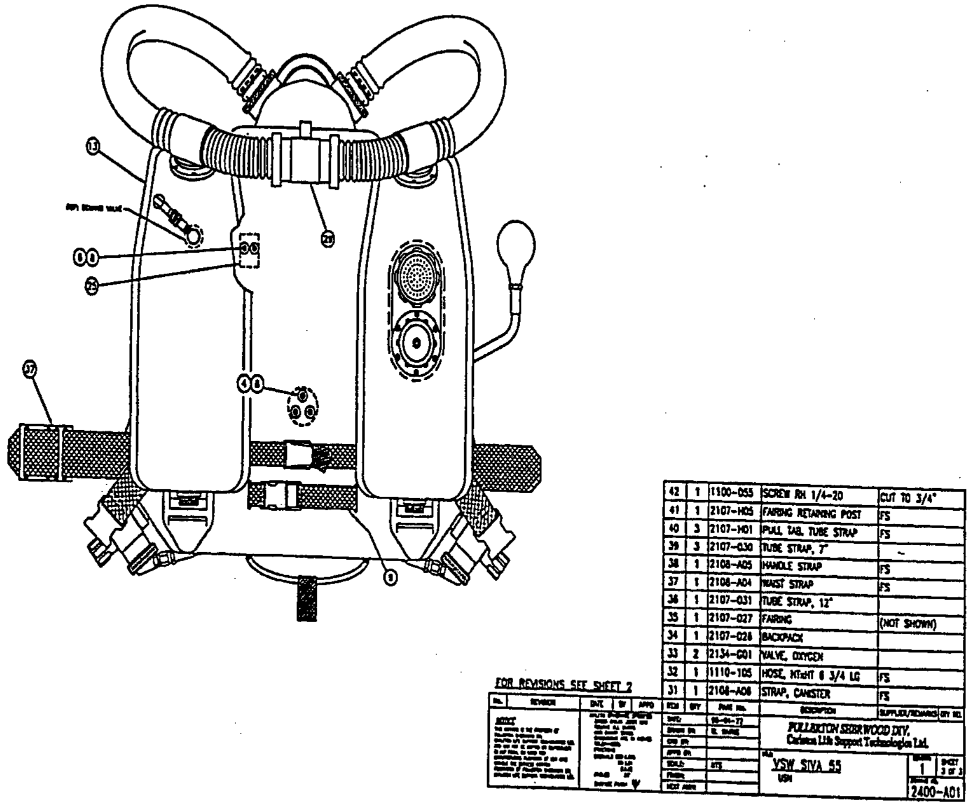

Figure 1. **Schematic of Sherwood-Fullerton Siva 55-VSW UBA Counterlung Arrangement.**

Most of the diver's exhaled gas is routed into the exhaust counterlung to be chemically scrubbed of carbon dioxide (see Figure 2), while the remainder escapes through the buoyancy control valve (BCV), or "pepper valve."

The UBA has an integral 18 liter capacity buoyancy control device / life vest (BCD) with a dedicated 0.2 liter, 3,500 psig air inflation cylinder. The BCD is worn between the diver's back and the UBA's backpack.

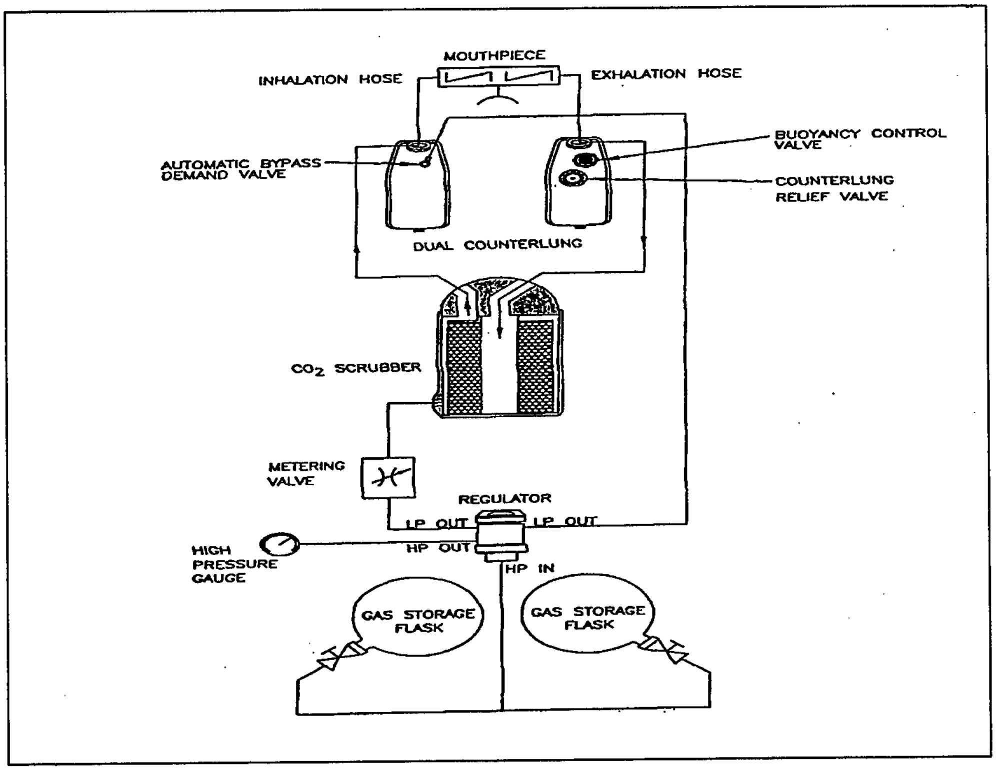

Figure 2. SIVA 55-VSW UBA Gas Flow Schematic

Table (1) provides a dimensional comparison between the MK 16 UBA, SIVA 55 UBA and the SIVA 55-VSW:

Table 1. UBA Dimension Comparison

UBA	Weight in Air (lbs / kg)	Length (in / cm)	Width (inches)	Depth (in / cm)
MK 16	64 / 29.1	23.6 / 60	14.9 / 37.8	10.5 / 26.7
SIVA 55	64 / 29.1	24 / 61	14.6 / 37.1	7.5 / 19
SIVA 55-VSW	51 / 23.2	20 / 50.8	19 / 48.3	10 / 25.4

PURPOSE

The purpose of this study was to verify that the SIVA 55-VSW meets the VSW MCM UBA performance specifications[3] as follows: Determine whether the UBA can maintain a sufficient O_2 fraction to support a working diver from the surface to 60 fsw (18.4 msw). Verify the UBA maintains a minimum partial pressure of oxygen (PO_2) of 0.3 atmosphere absolute (ATA) at 15 fsw (4.6 msw) and at 60 fsw (18.3 msw). Confirm that the average PO_2 did not exceed 1.3 ATA, and transient PO_2 does not exceed 1.7 ATA for more than 10 cumulative minutes across the entire dive mission.

Finally, while not directly tasked to do so, we collected data during the manned dives at test depths of 15 and 40 fsw (4.6 and 12.2 msw respectively) to determine CO_2 absorbent canister and UBA gas supply durations.

METHODS

GENERAL

Fullerton Sherwood provided five SIVA 55-VSW UBAs for evaluation. Testing was conducted in the 15 ft deep NEDU test pool, and at 40 and 60 fsw in the NEDU Ocean Simulation Facility (OSF). The water temperature was set at 77° ±3°F (25° ±1.7°C). Dress was to diver's comfort, and ranged from cotton shorts to quarter inch (6.4 mm) thick wet suits.

Navy-trained divers from NEDU learned to dive this UBA, then conducted familiarization dives in the test pool. These divers varied considerably in their experience with rebreathers, ranging from a single previous rebreather dive to over five hundred. At least 16 dives per test condition were conducted.

INSTRUMENTATION

We measured canister effluent O_2 and CO_2 using an EXTREL (Pittsburgh, PA) MS250 mass spectrometer. The sample gas flow rate was maintained between 80 and 100 ml/min actual. A Druck (Druck, Inc., New Fairfield, CT) pressure transducer mounted in the OSF dry chamber measured chamber pressure depth. Water temperature was monitored using a YSI 700 series thermistor probe. The following parameters were continuously monitored and logged every 15 seconds by our computerized data acquisition system (DAS) using Labview® (National Instruments Corporation, Austin, TX) data acquisition PC software: water temperature; zero time; actual time; and canister effluent O_2 and CO_2.

Two electrically-braked pedal ergometers (W.E. Collins, Braintree, MA) served to impose exercise on the divers. The ergometer frames were set at zero slope to emulate a swimmer's inclination. Divers' heart rates were monitored using a four-lead Quinton (Bothell, WA) Q-Tel Rehab continuous telemetry electrocardiography system.

We recorded the following UBA parameters: (1) starting and ending bottle pressures; (2) water collected from the inhalation and exhalation bags following each dive; (3) pre-dive, post-dive, and post-breakthrough UBA CO_2 absorbent weights; and (4) pre-dive, post-dive, and end-of-day UBA gas flow rates.

TEST PROCEDURES

General

All dives were conducted following standard USN diving practices[5, 6] using the manufacturer's specifications, except we used a 30% / 70% N_2 / O_2 mix for all dives vice the manufacturer's recommended 40% / 60% mix for depths deeper than 40 fsw. Divers purged their UBAs and lungs of air on the surface by squeezing the counter lung as flat as possible, lifting the knob of the counterlung relief valve to dump gas, while simultaneously exhaling forcefully. They then re-inflated the counterlung using the bypass valve, descended to the bottom of the test pool, and then repeated the purge procedure[7, 8]. The manufacturer does not require this additional purge on the bottom, but we employed this additional purge to expedite bringing the UBA's O_2 levels to an operational steady state.

Before diving each test day we calibrated all instruments and verified gas sample lines and electrical signals from each candidate UBA's umbilical line. After the UBAs were pre-dived, we again checked the instruments and calibrated as needed. At the end of each test day, we performed post-dive calibration checks to ensure the instruments remained within standards.

Divers received a pre-dive brief from the Diving Watch Supervisor (DWS) immediately before deployment, who directed them to go 'on gas' and perform the manufacturer-prescribed surface purge described above. "Zero" time was logged when the diver went 'on gas.' The diver conducted in-water checks and ensured the BCV was in the fully closed position before leaving surface.

Once on the bottom, the BCV was adjusted to approximately one-quarter open during earlier dives to minimize respiratory resistive effort by keeping the breathing bags inflated about half full. Set this way, the breathing bags would usually vent through the pepper valve on each exhalation while the diver remained on the bottom. Although unmanned testing was conducted with a BCV setting of half open, for manned testing divers were allowed to set the BCV to "diver comfort," which for most divers was one-quarter open.

The same UBA was dived by successive divers until the O_2 supply dropped below 290 psig (20 bar), or the canister effluent CO_2 exceeded 0.5% surface equivalent volume (SEV) for five minutes. These cut-offs were based on the manufacturer's recommendations which we employed to concurrently collect manned canister and bottle duration data. Canister duration times started when the first diver began breathing the UBA, and included all time divers were 'on gas' until the UBA CO_2 level reached termination criteria. Between dives, we immersed the UBAs' mouthpieces in disinfectant solution, then rinsed them in fresh water. We drained the breathing bags of all liquid, recording the volumes obtained. Turn-around times between successive divers on the same UBA were typically less than two minutes.

Test Pool Protocol

Upon reaching the bottom and completing the second purge, the divers usually remained at rest for five minutes, allowing the UBAs to stabilize, then mounted the ergometers and began pedaling at 60 $\pm$5 RPM with the initial pedal resistance level set at 50 watts. Divers continued to work for 30 minutes, allowing the UBAs to achieve steady-state O_2 levels.

Subsequently, the divers' workload was gradually increased across three minutes until reaching 75 watts. The divers then continued to work for an additional 30 minutes. The goal of selecting these workloads was to increase the divers' ventilatory rate from resting to near maximum ventilatory effort. After completing this phase, divers stopped work long enough to catch their breath, then informed topside when ready to leave bottom. All divers were required to purge the UBA in accordance with manufacturer's recommendation[2] prior to leaving the bottom, to ensure a sufficient PO_2.

OSF Protocol

For the initial 60 fsw testing, we pressurized the OSF as rapidly as possible, 30 to 45 fpm (9.2 to 13.8 mpm), and stopping 12 feet above the test depth to account for the wet chamber's water depth. If needed, the diver could restore the compression-depleted UBA counterlung gas volume by depressing the manual gas add valve; otherwise, counterlung volumes would ultimately equalize via the continuous 4.5 LPM gas mix injection.

Initially, divers worked for 10 minutes at 50 watts. If the UBA's PO_2 was above 1.3 ATA at the end of that period, the diver was directed to stop work and prepare to leave bottom. If UBA's PO_2 remained below 1.3 ATA, the diver continued pedaling for an additional 20 minutes. If no termination criteria were met during that period, the wattage was gradually increased to 75 watts, and the divers continued pedaling for an additional 30 minutes. Prior to leaving the bottom, all divers were required to purge the UBA following the manufacturer's recommendations[2].

Prior to completing the first dive, the second set of divers, tenders, and standby diver were briefed and transported to depth via "D" Chamber. The second set of divers used the same UBAs. This procedure was repeated until the CO_2 canister was expended.

Human Factors

Upon completing a dive, the divers completed a Human Factors Questionnaire (Annex A). These questionnaires addressed Use and Operation of the SIVA UBA, and were intended to elicit divers' subjective sentiments and overall impressions about diving this UBA. We also had the divers rate the breathing resistance levels they experienced after assuming different positional attitudes in the water, including head

up, head down, prone, and supine. Finally, during the test pool protocol, we solicited the divers' subjective evaluation and perceptions of the SIVA full face flask (FFM).

RESULTS

OXYGEN CONCENTRATIONS

Test Pool Protocol

During initial testing in the test pool, we conducted 21 test dives; the oxygen concentrations obtained during those dives are shown in Figure 3. During this series, the UBAs of 16 (76.2%) of these divers maintained O_2 concentrations above 34%. However, five (23.8%) of the divers breathed their UBAs down to a potentially hypoxic level, with four dropping to 21% and one reaching a steady state plateau of 24%.

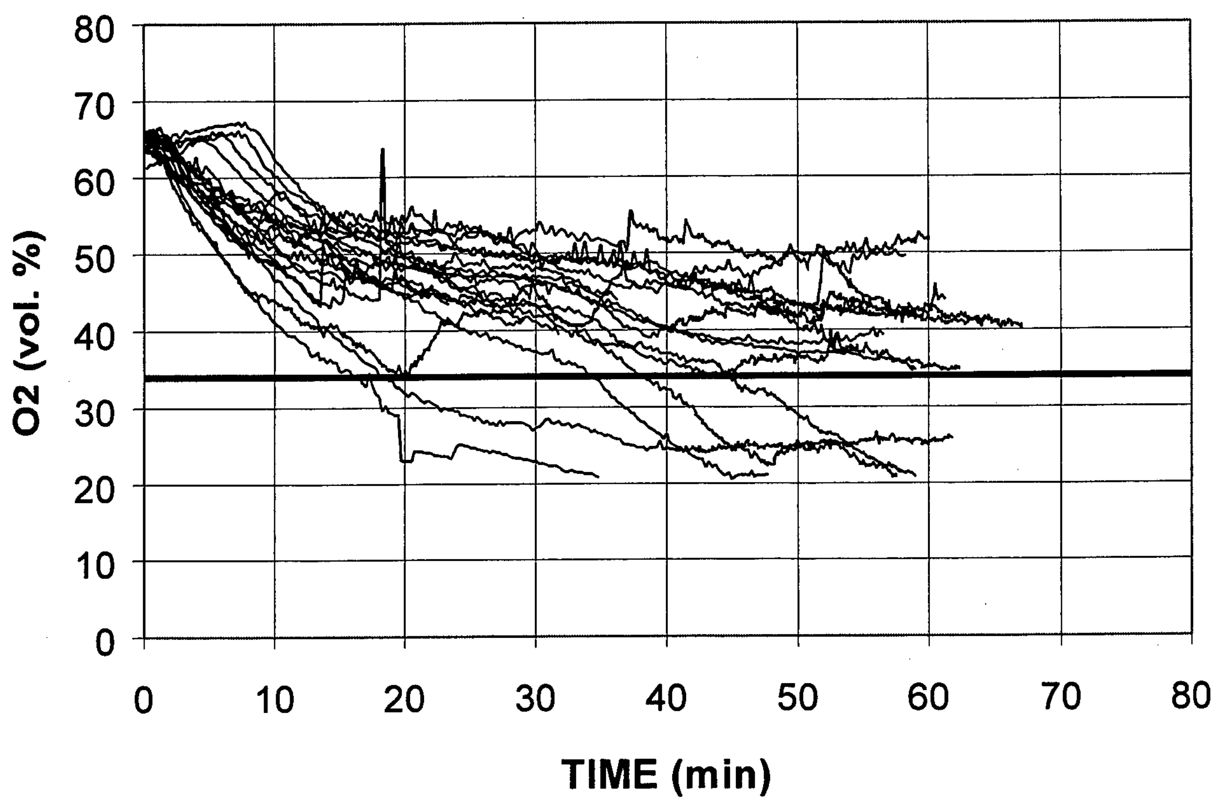

Figure 3. Test Pool Dives 15 -24 July 1998: UBA O_2 levels at 15 fsw across 21 dives with the "pepper valve" (BCV) set for diver comfort. Solid bold line represents 34%.

After reviewing these data with manufacturer representatives, we gleaned that the BCV setting might be critical for maintaining appropriate counterlung O_2 concentrations. To determine whether adjusting the BCV to allow more gas to burp off with each

exhaled breath would help maintain higher O_2 fractions, we conducted additional dives. Three of the five divers who had breathed the UBA down to hypoxic levels during the first series conducted another set of test pool dives. We used the same protocol as before, except we adjusted the BCV to half (vice one-quarter) open throughout the dives. As a result of having the BCV at the half open position, none of these divers approached their previous hypoxic levels. The data from this dive series are shown in Figure 4.

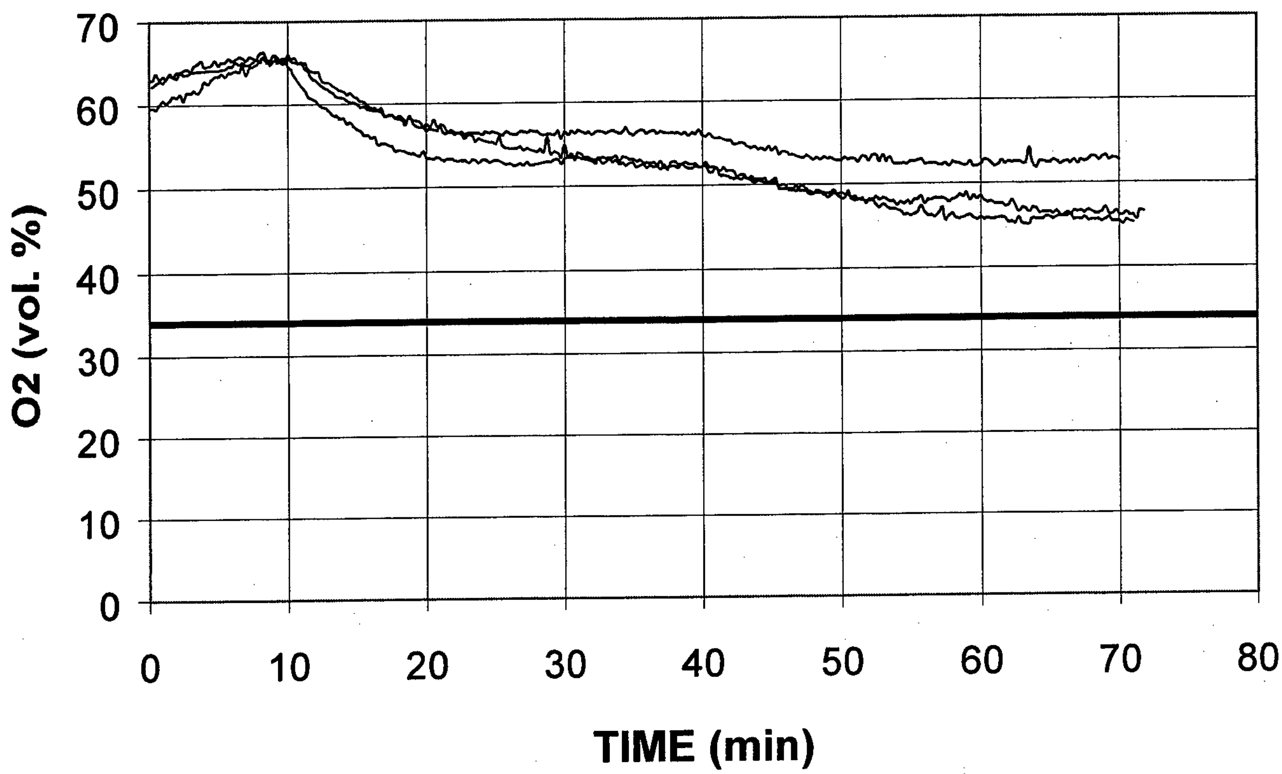

Figure 4. Test Pool Dives With "pepper valve" set at one-half open: SIVA 55-VSW UBA O_2 levels within the UBA with the "pepper valve" (BCV) set at 1/2 open using divers who reached hypoxic levels previously at 15 fsw. Solid bold line represents 34%.

<u>OSF Protocol</u>

We anticipated obtaining initial PO_2 levels as high as 1.97 ATA—based on the anticipated counterlung O_2 fraction around 70% at that depth—but we expected that working divers would breathe the UBAs down to acceptable levels. We therefore halted testing 60 fsw tests during the second set of dives after encountering continually high PO_2 levels. As shown in Figure 5, divers never breathed the UBAs below 1.3 ATA. One diver's PO_2 dropped to 1.32 ATA, but the average PO_2 across four dives was 1.63 ATA over a cumulative dive time of 187.4 minutes. Work rates varied from resting (35.8 minutes), 50 watts (97.7 minutes), and 75 watts (53.9 minutes).

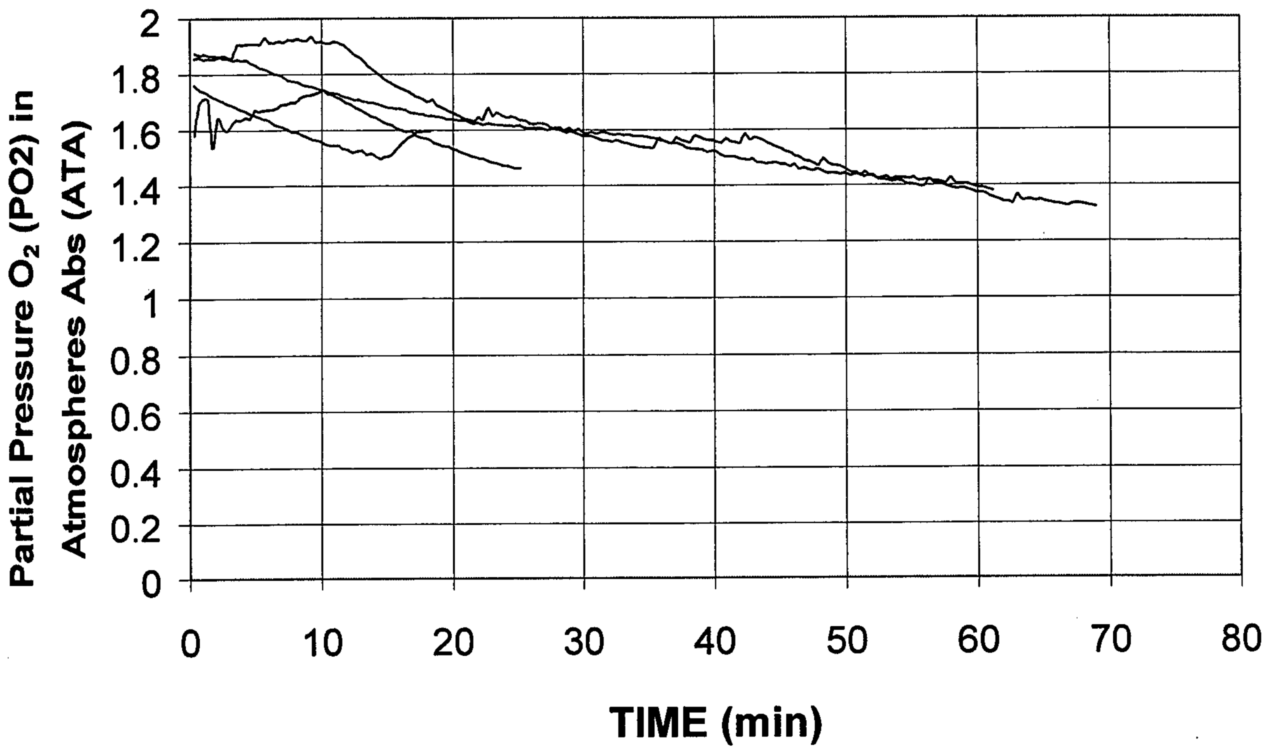

Figure 5. PO_2 Levels at 60 fsw OSF: SIVA 55-VSW UBA PO2 levels during OSF Testing at 60 fsw. Two dives were terminated before 30 minutes due to increased risk of central nervous system (CNS) O_2 toxicity.

Subsequent discussions with Navy EOD representatives determined that a 40 fsw operation—with possible excursions to 60 fsw—represents a more realistic VSW mission scenario. We subsequently modified the test protocol and resumed OSF testing at 40 fsw to simulate this profile. We also directed the divers to remain at rest for 10 minutes after reaching the bottom before commencing the ergometer exercise protocol. This strategy simulated a worst case scenario, where low oxygen consumption by resting divers would amplify the UBA's O_2 fraction. Our termination criteria allowed the dives to continue if UBA PO_2 remained between 1.3 and 1.7 ATA during the 10 minute resting phase. However, the dive was terminated if after 10 minutes of work the PO_2 did not drop below 1.3.

We completed 18 dives at 40 fsw. One dive was aborted due to a UBA malfunction. Of the remaining 17, eight (47%) of the divers' UBA PO_2 failed to drop below 1.3 ATA after 10 minutes of exercise (20 minute dive time = 10 minutes at rest + 10 minutes exercise), while seven (41.2%) completed the entire protocol. The remaining two divers were halted shortly after completing the 50 watt exercise segment due to canister and gas depletion. The data from this series are shown in Figure 6.

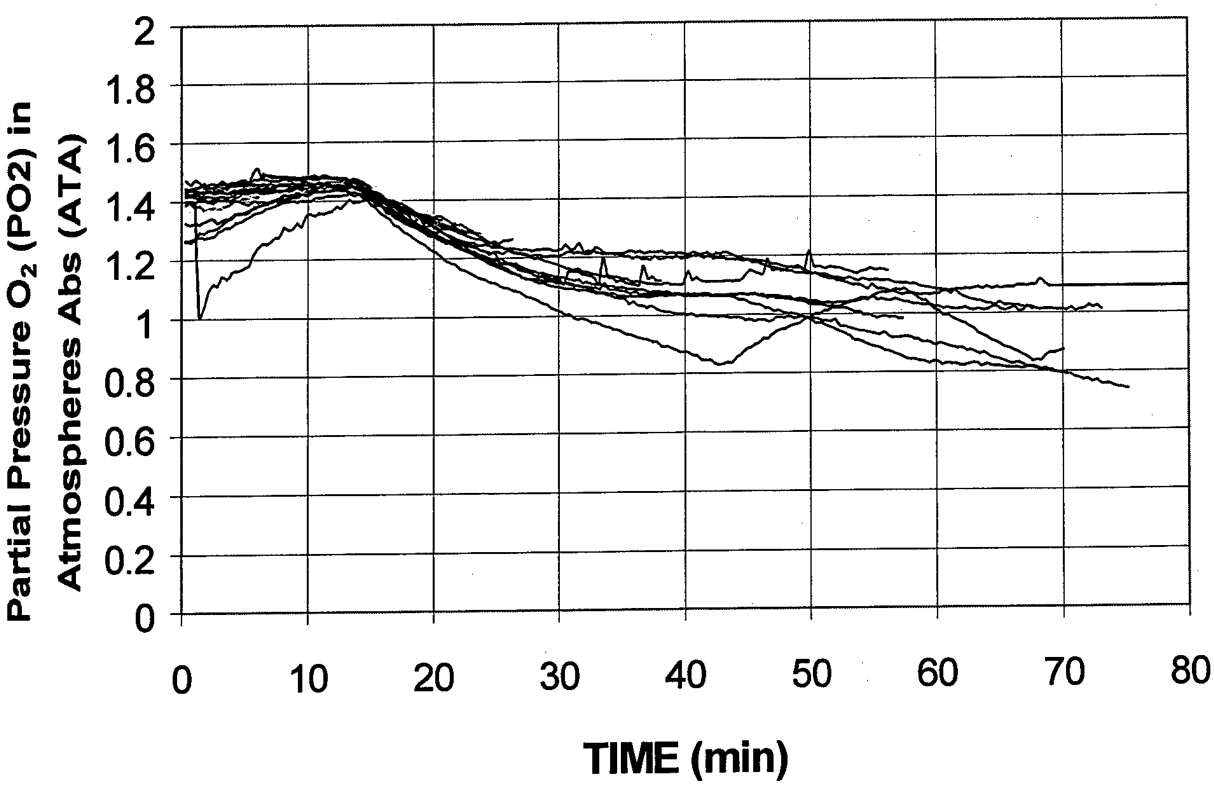

Figure 6. PO_2 **Levels at 40 fsw OSF: SIVA 55-VSW UBA** PO_2 **across 17 dives during OSF Testing at 40 fsw. All dives were conducted with the "pepper valve" set to diver comfort.**

The average PO_2 across 17 dives was 1.34 ATA with a range of 1.09 – 1.45 ATA over a cumulative dive time of 766.9 minutes. Work rates varied from resting (186.3 minutes), 50 watts (383.1 minutes), and 75 watts (197.5 minutes). Average PO_2 during the 10 minute resting period taken, as the worst case scenario, was 1.41 ATA.

CANISTER DURATIONS

Test Pool Protocol

We completed five canister duration tests during the test pool dives. Canisters lasted between 142.2 and 194 minutes, the average being 172.9 minutes. Table 2 shows the five individual dive data. These canister durations were determined by using total dive time on a particular canister. As a result, the work rate varied from resting to as high as 75 watts.

Table 2. Manned Canister Duration Runs (Test Pool).

DATE	DEPTH	TOTAL (min)
16 JUL 98	15 fsw	142.23
21 JUL 98	15 fsw	160.87
22 JUL 98	15 fsw	186.46
22 JUL 98	15 fsw	180.04
23 JUL 98	15 fsw	194.34
19 AUG 98	40 fsw	226.20
19 AUG 98	40 fsw	240.40
Total time in minutes reflects the accumulated time on a particular UBA from the time the UBA was initially breathed until CO_2 levels exceeded the termination criteria of 0.5 SEV for five minutes. All time on the UBA was included, and as a result work levels varied. Time shown included: resting (usually at least five minutes), pedaling the cycle ergometer at 50 watts (30 minutes) and pedaling at 75 watts (30 minutes).		

OSF Protocol

We only completed two canister duration tests during the 40 fsw OSF dives, since we repeatedly reached the high PO_2 termination criterion. Those durations were 226.2 and 240.4 minutes, shown in Table 2. One UBA's canister broke through about five minutes before the gas supply was depleted to termination pressure. The other UBA's gas supply dropped to termination pressure before canister breakthrough, but CO_2 levels were rising rapidly at that point. Again, work rates varied from resting to as high as 75 watts.

EXERCISE WORK RATES

Most divers indicated that the 50-watt workload was not particularly difficult, but finishing the 75-watt work protocol constituted quite a workout. While we didn't compute oxygen consumption (VO_2) rates during this series, past and ongoing research at NEDU indicate that working divers typically consume between 1.0 to 1.5 liters per minute O_2 (LPM VO_2)[9]. Pedaling underwater at 50 watts produces analogous metabolic needs of a heavy working diver, (i.e., 1.0 to 1.5 LPM VO_2), while 75 watts approximates a very heavy working diver's oxygen consumption levels (i.e., 1.5 to 2.0 LPM VO_2)[10].

WATER ACCUMULATION IN THE UBA COUNTERLUNGS

During some of the earlier dives, many divers complained of excessive water accumulation in the counterlungs. One diver's UBA counterlungs possessed so much liquid that we tested for chlorine content, to determine whether pool water was leaking into the UBA. That test proved negative for chlorine. During the 40 fsw dive series we paid particular attention to counterlung liquid accumulation, measuring and recording fluid levels in both bags from 22 dives; these data are shown in Table 3. The average dive time was 63 minutes, ranging between 32 and 105 minutes. Generally, only a small amount of liquid accumulated in the inhalation bag, while on average 18.8 ml was recovered from each exhalation bag, with one yielding 65 ml.

Table 3. Water Accumulation in the Counterlungs.

DATE	DIVE TIME (hours)	INH (ml)	EXH (ml)	CUMULATIVE (ml)
8/18/98	1:41	0	0	0
8/18/98	1:45	0	0	0
8/18/98	0:43	0	35	35
8/18/98	0:33	0	10	10
8/19/98	1:31	0	50	50
8/19/98	1:26	3	>50	750
8/19/98	1:15	0	0	0
8/19/98	1:29	0	0	0
8/19/98	0:57	0	41	41
8/19/98	1:02	0	24	24
8/20/98	1:24	8	46	46
8/20/98	0:34	7	5	12
8/20/98	0:32	0	0	0
8/20/98	0:36	0	0	0
8/20/98	1:28	0	18	18
8/20/98	1:36	35	65	100
8/20/98	0:41	18	23	41
8/20/98	0:34	2	2	4
Average	**1:03 hrs**	**4.1 ml**	**18.8 ml**	**23.9 ml**

INH = inhalation counterlung, EXH = exhalation counterlung, AVG = average volume of fluid accumulating in the UBA counterlungs. All dives were conducted at 40 fsw.

HUMAN FACTORS EVALUATION

Thirty divers completed Human Factor Questionnaires (HFQs). Although not all divers completed every phase of the study, all were asked to complete an HFQ subsuming those phases where they did participate.

Tables 4, 5, and 6 respectively tabulate the results of the HFQs administered after the 15, 40, and 60 fsw dives. Overall ratings remained consistently at or above the "good" rating. The glaring exceptions to this concerned (1) the buoyancy of the hoses; (2) the ease of working in a vertical position considering the buoyancy of the hoses; and (3) mouth fatigue due to hose buoyancy. These three items were consistently rated as "adequate" to "not quite adequate."

Table 4. Use and Operation of SIVA 55-VSW UBA Human Factors Evaluation at 15 fsw.

	Question	AVG	(#divers)
1.	How would you rate the ease of donning the rig?	5.13	(24)
2.	How would you rate the ease of adjusting the straps to secure a good fit?	5.00	(23)
3.	How would you rate the ease of reaching and operating the gas bottle valves?	5.29	(24)
4.	How would you rate the ease of reaching and operating the bypass valve?	5.38	(24)
5.	How would you rate the overall buoyancy of the rig?	5.21	(24)
6.	How would you rate the overall comfort of wearing the rig?	5.33	(24)
7.	How would you rate the ease of descending to swim depth?	5.29	(23)
8.	How would you rate the ease of maintaining swim depth?	5.09	(25)
9.	How would you rate the ease of operating the breathing bag's adjustable exhaust valve?	5.25	(25)
10.	How would you rate the ease of operating the breathing bag's manual dump valve?	5.25	(24)
11.	How would you rate the ease of operating the buoyancy compensator power inflator?	5.15	(13)
12.	How would you rate the ease of operating the buoyancy compensator deflator toggles?	4.73	(16)
13.	How would you rate the ease of the swim, compared to a typical swim of this type?	4.84	(20)
14.	How would you rate the ease of conducting a controlled ascent with this rig?	4.83	(25)
15.	How would you rate the overall ease of working while in a vertical position, considering the buoyancy of the rig?	5.04	(25)
16.	How would you rate the buoyancy of the hoses?	4.43	(24)
17.	How would you rate the ease of working while in a vertical position, considering the buoyancy of the hoses?	4.71	(25)
18.	How would you rate mouth fatigue, due to hose buoyancy?	3.83	(24)
19.	How would you rate ease of doffing the rig?	5.08	(25)

Results showing average rating for each question. The rating system was 1= extremely poor, 2= poor, 3= not quite, adequate, 4= adequate, 5= good, 6= excellent. Numbers in parentheses indicated total number of divers responding to question.

Table 5. Use and Operation of SIVA 55-VSW UBA Human Factors Evaluation at 40 fsw.

	AVG	(#divers)
1. How would you rate the ease of donning the rig?	4.92	(14)
2. How would you rate the ease of adjusting the straps to secure a good fit?	4.69	(14)
3. How would you rate the ease of reaching and operating the gas bottle valves?	4.92	(14)
4. How would you rate the ease of reaching and operating the bypass valve?	5.08	(14)
5. How would you rate the overall buoyancy of the rig?	5.23	(14)
6. How would you rate the overall comfort of wearing the rig?	5.08	(14)
7. How would you rate the ease of descending to swim depth?	4.85	(14)
8. How would you rate the ease of maintaining swim depth?	5.00	(12)
9. How would you rate the ease of operating the breathing bag's adjustable exhaust valve?	5.08	(14)
10. How would you rate the ease of operating the breathing bag's manual dump valve?	5.08	(14)
11. How would you rate the ease of operating the buoyancy compensator power inflator?	4.78	(11)
12. How would you rate the ease of operating the buoyancy compensator deflator toggles?	4.70	(11)
13. How would you rate the ease of the swim, compared to a typical swim of this type?	4.83	(13)
14. How would you rate the ease of conducting a controlled ascent with this rig?	4.92	(13)
15. How would you rate the overall ease of working while in a vertical position, considering the buoyancy of the rig?	4.77	(14)
16. How would you rate the buoyancy of the hoses?	4.54	(14)
17. How would you rate the ease of working while in a vertical position, considering the buoyancy of the hoses?	4.31	(14)
18. How would you rate mouth fatigue, due to hose buoyancy?	3.46	(14)
19. How would you rate ease of doffing the rig?	4.85	(14)

Results showing average rating for each question. The rating system was 1= extremely poor, 2= poor, 3= not quite, adequate, 4= adequate, 5= good, 6= excellent. Numbers in parentheses indicated total number of divers responding to question.

Table 6. Use and Operation of SIVA 55-VSW UBA Human Factors Evaluation at 60 fsw.

	AVG	(#divers)
1. How would you rate the ease of donning the rig?	5.17	(6)
2. How would you rate the ease of adjusting the straps to secure a good fit?	5.17	(6)
3. How would you rate the ease of reaching and operating the gas bottle valves?	5.33	(6)
4. How would you rate the ease of reaching and operating the bypass valve?	5.20	(5)
5. How would you rate the overall buoyancy of the rig?	5.33	(6)
6. How would you rate the overall comfort of wearing the rig?	5.17	(6)
7. How would you rate the ease of descending to swim depth?	5.33	(6)
8. How would you rate the ease of maintaining swim depth?	5.33	(6)
9. How would you rate the ease of operating the breathing bag's adjustable exhaust valve?	5.17	(6)
10. How would you rate the ease of operating the breathing bag's manual dump valve?	5.50	(6)
11. How would you rate the ease of operating the buoyancy compensator power inflator?	5.00	(3)
12. How would you rate the ease of operating the buoyancy compensator deflator toggles?	4.33	(3)
13. How would you rate the ease of the swim, compared to a typical swim of this type?	5.00	(5)
14. How would you rate the ease of conducting a controlled ascent with this rig?	5.00	(6)
15. How would you rate the overall ease of working while in a vertical position, considering the buoyancy of the rig?	5.00	(6)
16. How would you rate the buoyancy of the hoses?	4.83	(6)
17. How would you rate the ease of working while in a vertical position, considering the buoyancy of the hoses?	4.83	(6)
18. How would you rate mouth fatigue, due to hose buoyancy?	3.83	(6)
19. How would you rate ease of doffing the rig?	5.50	(6)

Results showing average rating for each question. The rating system was 1= extremely poor, 2= poor, 3= not quite, adequate, 4= adequate, 5= good, 6= excellent. Numbers in parentheses indicated total number of divers responding to question.

Table 7 provides the test pool divers' ratings of the SIVA FFM. They consistently provided "adequate" to "good" ratings, except for overall comfort of wearing the rig; it was consistently rated as "not quite adequate."

Table 7. Use and Operation of SIVA FFM Human Factors Evaluation at 15 fsw.

Question	AVG	(#divers)
1. How would you rate the ease of donning the rig?	5.14	(14)
2. How would you rate the ease of adjusting the straps to secure a good fit?	5.21	(14)
3. How would you rate the ease of reaching and operating the gas bottle valves?	5.50	(14)
4. How would you rate the ease of reaching and operating the bypass valve?	4.64	(14)
5. How would you rate the overall buoyancy of the rig?	N/A	
6. How would you rate the overall comfort of wearing the rig?	3.36	(14)
7. How would you rate the ease of descending to swim depth?	4.29	(14)
8. How would you rate the ease of maintaining swim depth?	4.21	(14)
9. How would you rate the ease of operating the breathing bag's adjustable exhaust valve?	5.00	(14)
10. How would you rate the ease of operating the breathing bag's manual dump valve?	4.57	(14)
11. How would you rate the ease of operating the buoyancy compensator power inflator?	4.89	(14)
12. How would you rate the ease of operating the buoyancy compensator deflator toggles?	4.86	(14)
13. How would you rate the ease of the swim, compared to a typical swim of this type?	N/A	
14. How would you rate the ease of conducting a controlled ascent with this rig?	N/A	
15. How would you rate the overall ease of working while in a vertical position, considering the buoyancy of the rig?	N/A	
16. How would you rate the buoyancy of the hoses?	4.57	(14)
17. How would you rate the ease of working while in a vertical position, considering the buoyancy of the hoses?	4.86	(14)
18. How would you rate mouth fatigue, due to hose buoyancy?	4.27	(14)
19. How would you rate ease of doffing the rig?	4.40	(14)

Results showing average rating for each question. The rating system was 1= extremely poor, 2= poor, 3= not quite, adequate, 4= adequate, 5= good, 6= excellent. Numbers in parentheses indicated total number of divers responding to question.

Table 8 summarizes the open-ended essay questions, providing an impressionistic sentiment about the SIVA 55-VSW UBA. Again, the predominantly positive aspects of the UBA were the ease of set-up, the simplicity of the UBA itself, and the overall comfort wearing the UBA in the water. The negative commentary centered on the buoyancy of the mouthpiece hoses and the discomfort this produced. The onset of encountering buoyancy-provoked discomfort ranged from a few minutes to 50 minutes.

Table 8. Summary of Open-ended Essay Questions.

1. **What did you LIKE the most about this UBA?** Overall favorable comments by divers included comments such as "comfortable to dive," "easy to set-up," "easy to breathe" and "liked the simplicity of the rig."
2. **What did you DISLIKE the most about this UBA?** General consensus focused on the mouthpiece itself which most divers said was very uncomfortable, and on the fact that the hoses pulled upward because they were so buoyant in the water.
3. **Did the rig cause you any discomfort at any time? Describe.** Again, most comments here focused on the discomfort associated with the mouthpiece.
4. **How long were you wearing the rig before the discomfort became apparent?** This varied a little, from immediately up to 50 minutes, but in general was within 15 minutes.
5. **List those activities where you felt that the rig interfered with accomplishing diving tasks.** Most of these comments concerned performing tasks directly in front of the diver's chest area, and this was restricted due to the counterlungs, and the buoyant nature of the hoses.
6. **Please provide any additional comments about the rig that you think are important:** these comments ranged from reiteration of early responses (mouthpiece, hoses, etc.) to "cover does not stay on well and needs better latching arrangement," and "lengthen bottle whips and hose on pressure gauge."

Table 9, 10, and 11 respectively summarize the results of HFQ ratings made following the 15, 40, and 60 fsw dives. Of particular note is the overall dyspnea score obtained during the 60 fsw dives (Table 11), where the UBA is consistently rated below "adequate."

Table 9. Rated Breathing Resistance Levels at Rest in 15 fsw.

DIVER ATTITUDE	INHALATION RESISTANCE	EXHALATION RESISTANCE	OVERALL DYSPNEA SCORE
HEAD UP	5.10 (21)	4.87 (23)	4.50 (25)
HEAD DOWN	5.10 (21)	5.00 (23)	4.58 (25)
45° HEAD UP	5.17 (23)	4.91 (23)	4.63 (25)
45° HEAD UP	5.22 (22)	5.00 (23)	4.63 (25)
PRONE	5.23 (22)	5.00 (23)	4.67 (25)
SUPINE	5.17 (23)	5.00 (23)	4.58 (25)

The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

Table 10. Rated Breathing Resistance Levels at Rest in 40 fsw.

DIVER ATTITUDE	INHALATION RESISTANCE	EXHALATION RESISTANCE	OVERALL DYSPNEA SCORE
HEAD UP	4.83 (13)	4.83 (13)	4.08 (10)
HEAD DOWN	4.82 (12)	4.82 (12)	4.17 (12)
45° HEAD UP	4.73 (12)	4.82 (13)	3.91 (11)
45° HEAD UP	4.73 (12)	4.82 (12)	3.80 (10)
PRONE	4.91 (12)	4.82 (12)	4.17 (11)
SUPINE	4.82 (12)	4.82 (12)	4.25 (12)

The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

Table 11. Rated Breathing Resistance Levels at Rest in 60 fsw.

DIVER ATTITUDE	INHALATION RESISTANCE	EXHALATION RESISTANCE	OVERALL DYSPNEA SCORE
HEAD UP	5.60 (5)	4.60 (5)	3.80 (5)
HEAD DOWN	5.00 (5)	4.20 (5)	3.60 (5)
45° HEAD UP	5.20 (5)	4.40 (5)	3.80 (5)
45° HEAD UP	5.00 (5)	4.40 (5)	3.80 (5)
PRONE	5.00 (5)	4.20 (5)	3.60 (5)
SUPINE	5.50 (4)	5.00 (4)	4.00.(4)

The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

Tables 12, 13, and 14 respectively summarize the results of HFQ ratings of breathing resistance levels encountered at each test depth. Across the range of test depths, the divers rated breathing resistance levels at both work rates from "adequate" to "good."

Table 12. Rated Breathing Resistance 50 and 75 Watt Workloads in 15 fsw.

	LOWER WORK LEVEL	HIGHER WORK LEVEL
INHALATION RESISTANCE	5.04 (25)	4.77 (22)
EXHALATION RESISTANCE	4.79 (25)	4.64 (22)
OVERALL DYSPNEA	4.48 (25)	4.33 (22)
LEVEL OF CONFIDENCE DIVING THIS UBA DURING AN EMERGENCY	5.35 (24)	5.45 (21)

The Lower Work Level corresponds to 50 watts, and the Higher Work Level to 75 watts. The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

Table 13. Rated Breathing Resistance 50 and 75 Watt Workloads in 40 fsw.

	LOWER WORK LEVEL	HIGHER WORK LEVEL
INHALATION RESISTANCE	4.75(13)	4.73(12)
EXHALATION RESISTANCE	4.83(13)	4.82(12)
OVERALL DYSPNEA	4.14(13)	4.10(11)
LEVEL OF CONFIDENCE DIVING THIS UBA DURING AN EMERGENCY	5.27(12)	5.10(12)

The Lower Work Level corresponds to 50 watts, and the Higher Work Level to 75 watts. The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

Table 14. Rated Breathing Resistance 50 and 75 Watt Workloads in 60 fsw.

	LOWER WORK LEVEL	HIGHER WORK LEVEL
INHALATION RESISTANCE	4.40 (4)	4.20 (5)
EXHALATION RESISTANCE	4.40 (5)	4.20 (5)
OVERALL DYSPNEA	3.00 (5)	3.00 (5)
LEVEL OF CONFIDENCE DIVING THIS UBA DURING AN EMERGENCY	5.60 (5)	5.40 (5)

The Lower Work Level corresponds to 50 watts, and the Higher Work Level to 75 watts. The rating system for breathing resistance: 1=extremely poor, 2=poor, 3=not quite adequate, 4=adequate, 5=good, 6=excellent. The average results from questionnaire are shown, with the numbers in parentheses indicating the number of diver-subjects responding.

DISCUSSION

OXYGEN CONCENTRATIONS

Oxygen concentrations within the UBA varied as a direct function of diver work level and BCV setting. Additionally, failure to adequately complete a pre-dive purge increases the risk of encountering a hypoxic event, especially when combined with the high metabolic demand created by swimming against a strong current, handling heavy or bulky equipment, etc.

The manufacturer recommends using the 30% / 70% N_2 / O_2 mix for dives up to 40 fsw, and switching to 40% / 60% N_2 / O_2 for 60 fsw operations; we used 30% / 70% N_2 / O_2 across all test depths. In this study, we only allowed PO_2 to exceed 1.3 ATA for 10 minutes before aborting the dive; had that limit been extended to 13 minutes, all but one diver could have continued the protocol. Three additional minutes of exposure to this PO_2 is not believed to significantly elevate the risk for central nervous system oxygen toxicity. Although the maximum calculated PO_2 at 40 fsw using a 70% oxygen mix is 1.55 ATA, the highest PO_2 we encountered was 1.49 ATA. It should be noted that the only incident where PO_2 exceeded 1.4 ATA at this depth occurred during the protracted rest phase at the beginning of the dive, a strategy we implemented to create a worst case scenario. Operationally, the likelihood of experiencing such a scenario remains remote for EOD divers entering a minefield. Of note is the average PO_2 of 1.34 ATA calculated for all seventeen dives at 40 fsw.

The latest revision of the US Navy Diving Manual[11] authorizes Enriched Air Nitrox (EAN) divers' PO_2 to reach 1.4 ATA without Commanding Officer (CO) authorization. A CO can authorize EAN dives where PO_2 reaches 1.6 ATA. In this study, all but one of our working divers breathed the UBA PO_2 below 1.3 ATA within 13 minutes; we anticipate working EOD VSW divers' PO_2 levels will remain well within these guidelines.

CANISTER DURATIONS

The manned evaluation of the SIVA 55-VSW canister performance was a quick-look to determine if the UBA met the operator's design specification. The preliminary man-data suggests that the canister does not perform to specifications[3]. This specification states canister duration must be at least 130% gas supply duration. Refer to NEDU unmanned report[4] for canister durations.

COUNTERLUNG WATER ACCUMULATION

As with other UBAs of this type, water will accumulate in the SIVA 55-VSW MCM counterlung as the diver's warm, moist exhalations cool inside the UBA, precipitating liquid in the breathing bags. In this study, fluid accumulation did not impede the operation of the UBA. Although this did not create any difficulties for the divers, many divers commented on how the accumulated liquid created gurgling sounds as they breathed. Rebreather divers may be better able to detect these sounds because they

are able to hear them because of the quiet operation of the UBA; moreover, they may be more attuned to these sounds since by their training they fully appreciate the disastrous consequences of a flooded semi-closed UBA.

HUMAN FACTORS EVALUATION

Overall the SIVA 55-VSW was rated as "good" or better in most areas of concern. Areas requiring improvement include the buoyancy of the mouthpiece hoses and the discomfort it creates in a diver's mouth. At 15 and 40 fsw the divers rated the UBA's breathing performance "adequate," no matter their positional orientation at rest, and at both work rates on the ergometer. However, at 60 fsw the UBA received "below adequate" ratings.

CONCLUSIONS

1. The Fullerton-Sherwood SIVA 55-VSW UBA meets the performance requirements of the EOD program office for the VSW MCM mission in the current test configuration with the exception of carbon dioxide absorbent canister duration.

2. Although the stated maximum operating depth for this UBA is 40 fsw, it is conceivable that divers may find themselves at deeper depths. We do not believe that a depth of 45 fsw places a working VSW diver at an unacceptably increased risk of oxygen toxicity, and should be tolerated. This will allow for variation in depth gauges and sonar depth soundings.

3. Changes have been made to the installed Buoyancy Compensator Device[12, 13] and the counterlungs are no longer considered "buoyancy compensating." Additionally, manipulation of this variable setting valve can significantly affect PO_2 levels, particularly at shallow depths. Therefore, we recommend changing the valve's nomenclature to "variable exhaust valve" (VEV), to more correctly describe the function of this valve.

4. EOD VSW divers need to remain aware of both the potentially hypoxic and hyperoxic conditions that they may encounter with this UBA due to inadequate purges and inappropriate position of the VEV.

RECOMMENDATIONS

We recommend that the SIVA 55-VSW be accepted and authorized for use by the VSW MCM detachment within the confines of the following recommendations.

1. All dives should be planned for depths not to exceed 40 fsw. In the event that depths greater than 40 fsw are anticipated, mission planners should consider the use of a different UBA (e.g., the MK 16). Although the manufacturer states that the SIVA 55-VSW may use different gas mixes—and specifically recommends using a 40% / 60% N_2 / O_2 gas mix for depths exceeding 40 fsw—the performance of this UBA has only been characterized using a 30% / 70% N_2 / O_2 gas mix.

2. All divers should complete a thorough UBA purge prior to entering the water and before descending, especially if they remain on the surface working for any length of time. Working at very shallow depths without purging the UBA could result in loss of consciousness. All divers should complete another UBA purge prior to leaving the bottom, especially if they have been working hard. Ascending without purging the UBA could result in loss of consciousness.

3. Excursion limits: Diving below 40 fsw should be avoided. However, any dive that exceeds 40 fsw but remains above 45 fsw (13.8 msw) is not considered an excursion, since the increased risk of oxygen toxicity is negligible. However, if a dive exceeds 45 fsw, the total cumulative time that a diver may remain below that depth is 10 minutes. At no time should this UBA be dove deeper than 50 fsw (15.3 msw).

4. Canister durations for mission planning should use NEDU canister limit recommendations based on unmanned studies[4].

5. Bottle gas duration for mission planning should use NEDU recommended times based on unmanned studies[4].

6. Change nomenclature of "buoyancy control valve (BCV)" to "variable exhaust valve (VEV)" to accurately reflect its function, and avoid confusing it with the integral buoyancy compensator.

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